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DESIGN AND STRENGTH CALCULATION OF
COMPONENTS IN STEAM AND GAS TURBINES

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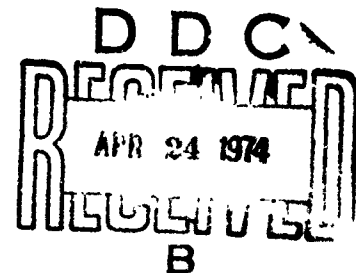
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DESIGN AND STRENGTH CALCULATION OF COMPONENTS IN STEAM AND GAS TURBINES

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Section 7. Erosion of steam turbine blades and related parts

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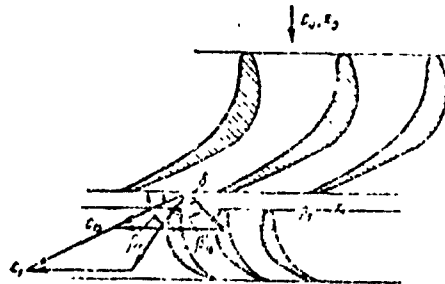
The blades of low-pressure stages in condensing steam turbines operated by the usual wet steam are subject to erosion generated by the mechanical effect of water particles and particularly by cavitation, i.e., rather substantial forces which cause damage to the metal may emerge with the onset of cavitation [8]*.

* Number refers to listing in bibliography.

Water drops formed by the expansion of saturated steam are carried away by the steam but do not reach the average rate of the steam flow. Consequently, the inlet angle of water particles to the blades in their relative motion turns out greater than that of steam particles (figure 51).

Impact on blades of water particles in the flow of wet steam: rate and inlet angle with index b pertain to water particles.

FIGURE 51



Erosion intensity grows with an increase of:

- a) the difference in the rates of steam and water, which becomes greater, particularly with an increase in peripheral speed;
- b) the impact angle δ of those particles relative to the leading edge of the blades; and
- c) the size of the water droplets.

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The large axial clearance in the flow-through section lowers the erosion intensity since there is an increase in time in which the flow of water particles accelerates.

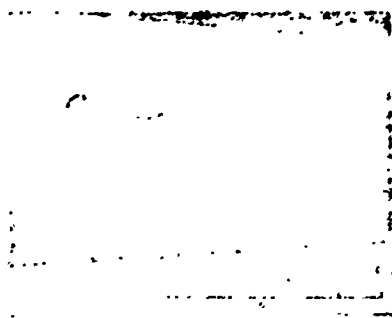


FIGURE 52

Eroded blade after 3,400 hours of operation.

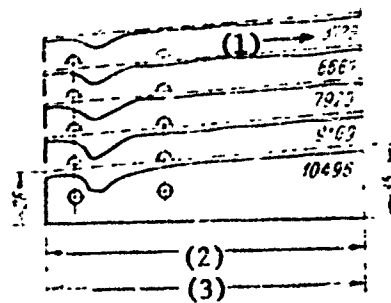


FIGURE 53

The increase of blade erosion as the time of blade use is increased. (1) - hours of operation; (2) - length of conical part: 160 mm; (3) - total length: 320 mm.

Erosion attacks only the blade area at its tip since the water drops are thrown by centrifugal force to the blade's periphery. The corrosion of blade material in this area may reach a substantial level.

The tip of an eroded blade is shown in Figure 52, while the nature of erosion variation as a function of time is shown in Figure 53. The blade was partially damaged by erosion already after 3,728 hours of operation. Subsequently, the deterioration of the material continued, although not at such a quick rate as during the first hours of operation (this is due to thickening of edges as they wear down), and after 10,496 hours, erosion damage spreads to the area beneath the binding wire and to almost half of the blade's width at the tip. The blades were made of a 5% nickel steel and operated in a steam with a 10% moisture.

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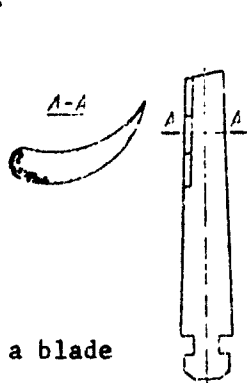


FIGURE 54

Stellite plating on a blade

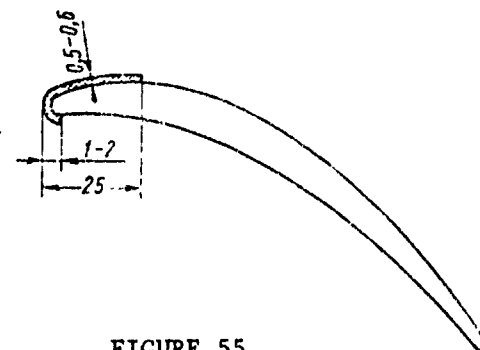


FIGURE 55

Electric spark surfacing of a KhTGZ blade with hard metal

For combatting erosion, one must on the one hand increase the surface hardness of blades and on the other hand design the flow-through section of the turbine with outlets for water which forms in the low-pressure stages.

Our industrial plants successfully employ stellite plates*

* VZK Stellite contains 60 to 65% Co, 25 to 28% Cr, 4 to 5% W, 2 to 2.5% Si, 1 to 1.2% C, and the rest Fe.

soldered or welded to the leading edges as shown in Figure 54. The plates are made of several parts and are welded along the length of the blade with gaps to allow for thermal deformations.

Surface hardening through electrolytic chrome-plating or electric spark surfacing with hard alloys is also employed. Spark surfacing of one of the cross-sections of a KhTGZ blade is shown in Figure 55.

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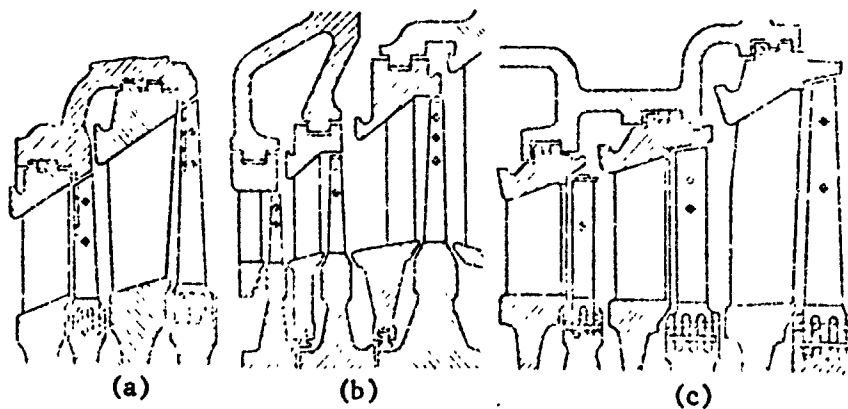


FIGURE 56

Arrangements for draining moisture:
 (a) - LMZ (Leningrad Metal Plant);
 (b) - KhTGZ (Khar'kov Turbogenerator Plant); (c) - NZL (Neva Machinery Plant).

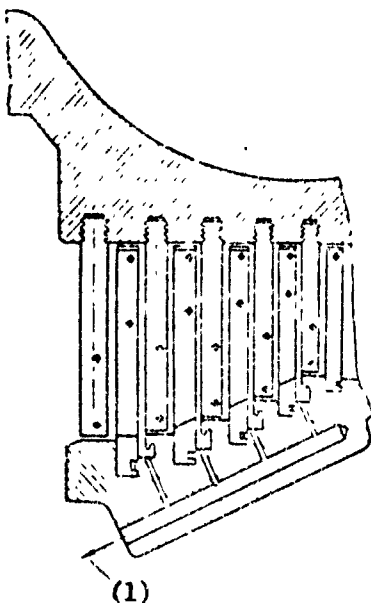


FIGURE 57

Arrangement for draining moisture in a reaction turbine with a drum rotor.
 (1) - to condenser.

Examples of some designs of turbine flow-through sections with outlets for generated water are shown in Figures 56 and 57.

In the design shown in Figure 56, water is partially drawn into annular chambers built in the space between the diaphragms and casing, from where it is discharged to a drain or condenser.

In the design (see Figure 57) with a drum rotor and reaction blading, moisture is removed by suction to a channel connected to the condenser.

Unfortunately, there is still not enough data which would permit an evaluation of the effectiveness of one or the other method of moisture separation. Apparently the designs of the type discussed allow separation of only 20 to 30% of moisture contained in the steam.

Section 16. Temperature of cooled turbine blades and thermal stresses

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As indicated in Section 6, the blades of high-temperature steam turbines (with $t_0 \geq 600^\circ\text{C}$) are cooled by lowered temperature steam which cools the blade roots (see Figures 41 and 42). Gas-turbine blades are cooled by dissipating heat into an air-cooled wheel, or else the roots are cooled directly by air, as for example, through the gaps of the pine-tree type blade root.

In all these cases, the average temperature of the blade profile over most of its height equals temperature t_e^* of gas slowed down in its relative motion before reaching moving blades:

$$t_e^* = t_0^* - \frac{c_1^2 - w_1^2}{2c_p} = t_0^* - \frac{u^2}{2c_p} \left(\frac{2 \cos \alpha_1}{\frac{u}{c_1}} - 1 \right), \quad (109)$$

in which t_0^* is the temperature in degrees of the slowed gas before the stage;

w_1, u, α_1 are the quantities known from thermal computations of the turbine; and

c_p is the gas specific heat in $\text{J}/(\text{kg} \times \text{deg})$.

It follows from equation (109) that the blade temperature drops with an increase of u and reduction of α_1 and $\frac{u}{c_1}$.

The average temperature along the height of a blade of uniform profile varies according to the expression [10]:

$$t = t_e^* + (t_0^* - t_e^*) e^{-kx}, \quad (110)$$

in which t_1 is the temperature in $^{\circ}\text{C}$ at the root cross-section of the blade;

$$k = \sqrt{\frac{\alpha_2 u_2}{\lambda f}}$$

x is the ordinate of the blade's length measured from the root section in meters;

α_2 is the coefficient of heat transfer from gas to the blade in $\text{w}/(\text{m}^2 \times \text{deg})$;

Fig 9

u_2 is the perimeter of the blade cross-section in meters;

λ is the heat conductivity of gas in $\text{w}/(\text{m} \times \text{deg})$; and

f is the area of the blade cross-section.

Temperature t_1 may be determined from the heat exchange conditions between the rim and the blade of the wheel [10]. The temperature for blades with a varying profile is discussed in technical literature [42]. The heat transfer coefficient α_2 may be taken on the basis of experimental data obtained during testing of stationary blade arrays [10 and 42]. This value must be increased by 20 to 30% when computing rotating blades.

The nature of the temperature change along the length of the blade is shown in Figure 97. It can be seen from it that the temperature along the entire length of the blade equals the temperature at the blade root only at very high heat conductivities of the material ($\lambda \rightarrow \infty$), when $k \rightarrow 0$. Even when $k > 5-10$, only a small part of the blade's length at the root is cooled. The greater α_2 and u_2 , the more poorly cools the blade; and the greater λ and f , the more effective the cooling. In the best case k is usually between 4 and 6; under unfavorable conditions, k may reach 25 and greater.

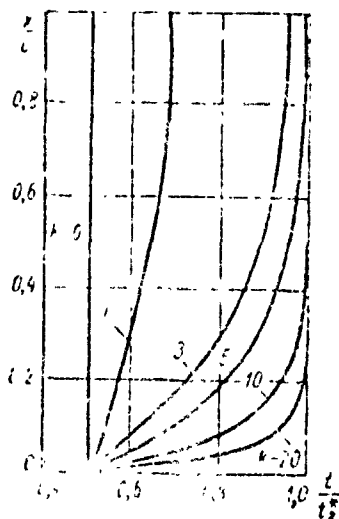


FIGURE 97

Temperature distribution along the blade height with a constant

$$\frac{t_1}{t_2} = 0.5$$

With gas flowing past the blade, the gas temperature (in reaction blading) generally drops. Irrespective of this, the heat transfer coefficient α varies along the profile and reaches a maximum at the leading and trailing edges. Therefore, the blade temperature along the profile is variable: its greatest values are observed at the edges. This temperature variation causes the development of temperature stresses in the blade which are proportional to the quantity $E \alpha \Delta t$, where E is the elastic modulus, α is the linear expansion coefficient, and Δt is the temperature difference between individual sectors in the cross-section, for instance, between the edge and the thickest part of the profile. These stresses, in high-temperature gas turbines, frequently cause cracks at the edges, particularly during transient conditions.

The temperature variation along the length of the blade also gives rise to the development of thermal stresses. The greatest stresses arise at the transition point between the root and the blade, i.e., at the point with the greatest rupture and bending stresses.

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A method of calculating thermal stresses for this case has been worked out by Ye. Ya. Gertsberg [37].

More effective than that discussed is internal air or liquid cooling of gas turbine blades.

Chapter IV. Materials for Blades. Selection of the Tolerable Stress

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Section 28. Requirements imposed on blade material

An analysis of the conditions in which moving blades operate and a study of typical breakdowns of blade systems established that the blade material must have the following characteristics:

- a) high strength at the working temperature of a blade;
- b) high ductility required for a uniform distribution of stresses over the entire area of the blade's cross-section;
- c) low sensitivity to stress concentration and the greatest possible vibration damping ratio;
- d) stable structure ensuring the immutability of mechanical properties during operation;
- e) resistance to corrosion due to the effect of gas or steam as well as oxygen in air;
- f) resistance to erosion; and
- g) favorable mechanical properties permitting the use of inexpensive methods of processing blades and ensuring an accurate production of profile dimensions and high surface finish.

Heat conductivity and the linear expansion coefficient of metals have a great significance for blades of high-temperature gas turbines. The greater the heat conductivity λ , the more uniform is

the blade's temperature field; the smaller the linear expansion coefficient, the lower are the thermal stresses which arise from non-uniformity of the temperature field (see Section 14).

In speaking about the strength characteristics of metals, it should be noted that only at blade temperatures up to approximately 400°C can one be satisfied with the data on the material's mechanical properties (ultimate strength, yield strength, etc.) which have been obtained during short-term testing for a given temperature.

As it was pointed out, metals under stresses lower than the yield strength undergo plastic deformation under a prolonged effect of loads, particularly in high temperature conditions. Also, under these same conditions, metals break down at a stress lower than the ultimate strength since, with an increase in the duration of the load application, the rupture strength drops. Thus, at high temperatures, the metals' strength depends not only on the magnitude of the mechanical stress but also on the duration of the load application to the metal.

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This suggests that at high temperatures the ultimate strength and yield strength cannot serve as strength criteria. In this case, the creep limit and rupture strength should be considered as the criteria. The endurance (fatigue) strength under a symmetrical cycle of σ_1 serves as the strength criterion when evaluating the fatigue strength of blades. Together with the yield strength and rupture strength, its value should be taken into consideration when selecting the blade materials. Like the former, the endurance strength also decreases with an increase in temperature. The fatigue strength is influenced considerably by the sensitivity of the material to stress concentration, which can be evaluated after comparing the endurance strength values for smooth (σ_1) and notched (σ_1)_N specimens.

Careful burnishing of blades, increasing the radii of the blade's transition to the stem, rounding off edges, increasing if possible the depression radii of the pine-tree blade roots, etc., are the effective means of countering stress concentrations in blades. The endurance strength depends on the condition of the blades' surface, and for that reason, it decreases in time as a result of blade corrosion and erosion.

It must be kept in mind that stresses in the material vary asymmetrically during blade vibrations, i.e., the steady tensile stresses due to the centrifugal forces are superimposed on the varying transverse stresses. Therefore, the appropriate methods [20] should be used in the design of blades for endurance.

The difficulty in carrying out these computations lies in the absence of the reliable data on the level of dynamic stresses in

blades. Proper evaluation of the margin of fatigue strength can be made only after experimental performance investigations.

Section 29. Materials for steam turbine blades

Soviet turbine construction plants employ exclusively stainless steels for turbine blades: for work at moderate steam temperatures (up to 450°C), chromium stainless steels 1Kh13 and 2Kh13 largely meet the requirements indicated in the preceding section. Under small stresses, these steels may be used even at a steam temperature of up to 550°C. /156

For higher temperatures steels 15Kh1MF (to 540°C), 15Kh12VMF or EI802 (to 580°C), and 1Kh12V2MF (to 580°C) may be recommended. These steels are also chromium stainless steels of the pearlite grade with the same small content of nickel as steels 1Kh13 and 2Kh13 but with molybdenum and vanadium additives, and also tungsten in the case of the last two steels (EI802 and 1Kh12V2MF).

The austenitic steels EI123, EI405 (also EI403 steel similar to them in terms of its properties), and EI612K are characterized by even greater heat resistance. Steel EI612K is recommended for temperatures to 700°C. This group belongs to chromium steels with a high content of nickel (up to 14% in steels EI123 and EI405 and up to 30% in steel EI612K) and various additives, some of which (e.g., tungsten, molybdenum, cobalt) increase the strength at high temperatures and others (titanium, niobium) guard against the tendency toward intercrystalline corrosion.

The chemical composition and some physical constants and mechanical properties of the above steels are shown in table 8.

It should be noted that the mechanical properties of chromium steels depend highly on the heat treatment method. For instance, the ultimate strength and proportional limit of 2Kh13 steel can be substantially increased by lowering the temperature of tempering. In this case, however, there is a drop in the elongation and impact strength, which is unsuitable for turbine blades with their large dynamic stresses due to bending and variable loads.

Chrome-nickel steels EI123 and EI405 have a far higher heat and corrosion resistance than chromium steels do. They are also characterized by high plasticity; however, their yield point at room temperature is considerably smaller than that of steel 2Kh13. It may be noted here that the nature of heat treatment of steel EI123 does not have such a strong effect on the steel's mechanical properties as in the case with steel 2Kh13.

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The elasticity modulus E of materials drops with a rise in temperature, which lowers the frequency of natural oscillations; as a rule, thermal conductivity λ and the linear expansion coefficient α increase. It should be noted that α of austenitic steels is considerably greater than that of pearlitic steels, while λ is practically the same at temperatures of 500° to 600°C.

rupture strength
creep strength

- (1) - EI802; (2) - EI405;
(3) - EI802; (4) - EI405;
(5) - EI612K; (6) - EI457B;
(7) - EI607A; (8) - EI893,
(9) - Mn/m²

Stellite plates, which have the following chemical composition: 65% Co, 25% to 28% Cr, 4% to 8% W, 2% to 2.5% Si, 1% to 2% C, and the rest Fe, are soldered to the leading edges of blades from the last stages of condensing turbines for an improved resistance to erosion. The hardness of the plates is HRC ≥ 40 . Silver solder is used for soldering.

TABLE 8 (on following pages)

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Chemical Composition and Mechanical and Physical Properties of Materials
Used for the Fabrication of Blades of Compressors and Steam and Gas
Turbines

(1) - Brand of material and its approximate chemical composition in %;
(2) - Tolerable temperature* in °C; (3) - Temperature of test sample in °C;
(4) - Physical properties; (5) - ρ in kg/m³; (6) - λ in w/m x deg;
(7) - $\alpha \times 10^{-5}$ in deg⁻¹; (8) - $E \times 10^{-6}$ in Mn/m²; (9) - Mechanical
properties; (10) - σ_v [tensile strength] in Mn/m²; (11) - $\sigma_{0.2}$ [yield
point] in Mn/m²; (12) - δ_g [relative elongation] in %; (13) - ψ [relative
contraction] in %; (14) - a_k in k-j/m²; (15) - BHN; (16) - Rupture strength
in Mn/m²; (17) - Creep in Mn/m²; (18) - σ_{-1} (over 10^7 cycles) in Mn/m²;
(19) - Remarks; (20) - 1Kh13 (Zh1); (21) - 2Kh13 (Zh2); (22) - 15Kh11MF;
(23) - 15Kh12VMF (EI802); (24) - 1Kh12V2MF (EI756); (25) - 2Kh14N14V2S2T
(EI123); (26) - Kh16N13M2B (EI405); (27) - Compressor and steam turbine
blades. Shroudings; (28) - Compressor and steam turbine blades; (29) -
Steam turbine blades; (30) - Same;

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(31) - Kh15N70V5M4Yu2TR (EI765); a - Nickel-based; (32) - Kh14N18V2BR1
(EI725); (33) - EI612K; (34) - Kh20N77T2YuR (EI437B); a - Nickel-based;
(35) - EI607A; a - Nickel-based; (36) - EI893; a - Nickel-based;
(37) - Gas turbine blades; (38) - Steam and gas turbine blades.

* The question of tolerance of any temperature is resolved by comparing the stress levels in a blade with the characteristics of a metal at the blade's working temperature. The figures shown in Table 8 are approximate. It is necessary also to take into account other metal characteristics indicated in reference literature (e.g., heat resistance, specifications, etc.).

** The figures in this column pertain to the linear expansion coefficient obtained within a temperature range from 20° - 25° to the level indicated in the third column of the table.

*** These figures pertain to $\alpha_{2/10^4}$.

(1) Марка материала и его химический состав	(2) Допускная темпе- ратура в °С	(3) Температура испи- тания	(4) Физические свойства					(9) Механические свойства					(18) Испытание на удар					(19) Применение		
			(5) ρ в кг/м ³	(6) λ в см/м·град	(7) $\alpha \cdot 10^{-6}$ в град	(8) $E \cdot 10^{-6}$ в МПа	(9) σ в МПа	(10) $\sigma_{0.2}$ в МПа	(11) $\sigma_{0.2}$ в МПа	(12) δ в %	(13) ψ в %	(14) $\sigma_{\text{в}} \cdot 10^{-3}$ в МПа	(15) НВ	(16) Длительная прочность в МПа			(17) $\sigma_{\text{в}} \cdot 10^{-3}$ в МПа			
														σ_{10}	σ_{10}	σ_{10}				
(20) 1X13 (Ж1) 9,15C; 0,6Mn; 0,6Si; 13Cr; 0,6Ni	450	20 200 400 500	7750	27,6 27,6 27,6 27,2	— 10,45 11,4 11,8	0,206 0,196 0,19 0,17	610 530 490 360	410 370 360 270	410 370 360 270	22 16 16,5 18	60 60 58 64	1080 — 1950 2350	180	— — 370 210	— — 330 185	— — 290 95	— — 121 56	370 — 265 220	Лопатки ком- прессоров и па- ровых турбин. Бандажи	
(21) 2X13 (Ж2) 0,2C; 0,6Mn; 0,6Si; 13Cr; 0,6Ni	450	20 200 400 500	7750	27,6 27,6 27,6 27,2	— 10,4 11,4 11,8	0,218 0,208 0,189 0,16	710 — 520 430	510 — 400 360	510 — 400 360	21 — 16,5 32,5	65 — 58,5 75	640— 1700 — 2450	200	— — 370 190	— — 320 157	— — — 157	— — — 47	370 — 255 235	Лопатки ком- прессоров и па- ровых турбин	
(22) 15X11MФ 0,15C; 0,6Mn; 0,5Si; 11Cr; 0,6Ni; 0,4V; 0,6Mo	540	20 200 400 500 550	7750	— — — — —	— 10,6 11,3 11,7 11,8	0,224 0,209 0,189 0,176 —	760 670 580 500 520	590 540 480 420 430	590 540 480 420 430	38 36 33 40 40	66 — — — —	760 980 1230 1080 1080	217— 241	— — — — 196	— — — — 140	— — — — 90	— — — — —	— — — — —	Лопатки па- ровых турбин	
3) 15X12BMФ (ЭИ802) 0,15C; 0,6Mn; 0,3Si; 12Cr; 0,6Ni; 1W; 0,6Mo; 0,2V	580	20 200 400 550 600	7850	24,7 25,6 26,4 27,0 27,2	— 10,5 — 11,4 11,7	0,212 0,202 0,19 0,165 —	870 740 670 500 370	740 640 590 450 350	740 640 590 450 350	15 14 14,5 19 23	58,5 66 62 71,5 88	930 1520 1470 1370 1320	— — — — —	— — — 245 150	— — — 216 127	— — — — —	— — — 98 49	370 — — — —	То же	
4) 1X12B2MФ (ЭИ756) 0,12C; 0,7Mn; 0,3Si; 12Cr; 0,8Ni; 2W; 0,7Mo; 0,3V	580	20 600	7830	25,0 21,0	— 13,8	0,208 0,261	870 440	720 415	720 415	17,7 21	54,7 85,3	1350 1510	— —	— 143	— 128	— —	— —	— 44	— —	То же
5) 2X14H14B2C2T (ЭИ123) 0,2C; 0,6Mn; 2Si; 15Cr; 13Ni; 2W; 1Ti	600	20 400 500 600	7870	— — — —	— 17,2 17,4 17,8	0,193 0,169 0,161 0,152	660 470 480 450	300 216 206 210	300 216 206 210	50 27 30,5 27	50 50 57,5 53	1860 2160 1960	137 157	— — — 103	— — — 74	— — — 157	— — — 118	320 — — —	То же	
6) X16H13M2B (ЭИ405) 0,1C; 0,5Mn; 1Si; 17Cr; 14Ni; 1Nb; 2Mo	600	20 500 600 700	7960	14,2 21,7 23,0 24,6	— 17,4 17,8 18,2	0,202 0,164 0,155 —	550 460 420 —	245 157 147 —	245 157 147 —	30 31 29 —	35 33 34 —	960 980 880 —	137— 172	— — — 196	— — — 59	— — — 22	— — — 88	— — — 34	То же	

TABLE 8

Марка материала и его приварочный химический состав в %	Допустимая темпе- ратура в °С	Температура испи- тания в °С	Физические свойства				Механические свойства										Примечание		
			ρ в г/см ³	λ в см/(м·град)	$\alpha \cdot 10^{-6}$ в град ⁻¹	$E \cdot 10^{-6}$ в МПа/м ²	σ_g в МПа/м ²	$\sigma_{0,2}$ в МПа/м ²	R_m в %	ψ в %	σ_K в кг/см ²	III	Длительная прочность в МПа/м ²		Ползучесть в МПа/м ²			σ в 10 ⁻⁴ в 10 ³ ч	σ в 10 ⁻⁴ в 10 ⁵ ч
													σ_{10^5}	σ_{10^3}	σ в 10 ⁻⁴ в 10 ³ ч	σ в 10 ⁻⁴ в 10 ⁵ ч			
(31) X15HT0B5M4H02TP (31H765) 0,1 C; 0,5 Mn; 0,5 Si; 15 Cr; 4 Mo; 5 W; 1 Ti; 2 Al; 3 Fe; 0,01 B Ni — основа а	700	20 565 700 800	8600	8,3 24,5 29,0 —	— 14,3 15,1 —	0,216 0,19 0,177 —	1070 1000 900 560	690 610 570 490	30 26 22 19	32 24 31 49	880 880 880 980	245— 324	— 440 590 230 80	— — 200*** 160***	— — — —	— — — —	Лопатки газозовых турбин (37)		
(32) X14H18B2EP1 (3H726) 0,1 C; 2 Mn; 0,6 Si; 14 Cr; 19 Ni; 2,5 W; 1 Nb; 0,02 Ce; 0,025 B	670	20 600 700	8100	15,9 23,0 25,0	15,2 18,1 18,5	0,204 0,157 0,149	570 430 350	240 180 170	39 29 31	46 52 55	1230 1760 1720	126— 140	— 260 230	— 170 140	— 250 120	— 170 65	То же		
(33) 3H612K 0,1 C; 1 Mn; 0,5 Si; 15 Cr; 36 Ni; 1,4 Ti; 3 W; 4 Co; 0,01 B	700	20 550 650 700	8200	12,0 21,0 22,8 23,8	— 15,9 16,3 16,5	0,189 0,159 0,151 0,147	680 550 475 490	360 320 280 350	28,5 30 31,5 18	37 41 43,5 30	1420 — 1270 1810	220	— — — —	— — 130 90	— — 205 160	— — 175 135	Лопатки паровых и газозовых турбин (38)		
(34) X20H77T2OP (3H437B) 0,06 C; 0,6 Mn; 1 Si; 20 Cr; 2,5 Ti; 0,8 Al; 1 Fe; 0,01 B Ni — основа а	700	20 500 700 800	8200	19,2 26,4 29,2 32,6	— 13,9 14,6 15,1	0,196 0,157 0,147 0,127	1000 860 830 520	650 540 520 460	18 31 27 15	16 31 30 27	590 540 490 880	245— 310	— 465 185 ~80	— — — —	— — — —	360 — — 235	Лопатки газозовых турбин		
(35) 3H607A 0,05 C; 1 Mn; 0,8 Si; 16 Cr; 1,6 Ti; 1,5 Nb; 0,5 Al; 3 Fe Ni — основа а	700	20 650 700 750	8300	12,5 25,2 26,3 27,6	— 15,2 15,6 16	0,217 0,18 0,175 —	1080 — — 660	650 — — 540	28 — — 14	60 — — 25	1470 — — —	~250	— — 220 130	— — 170 100	— — — —	— — — 65	То же		
(36) 3H593 Ni — основа а	750	20 750 800	— — —	— — —	— — —	0,218 0,17 0,162	980 680 660	750 540 490	27 20 25	32 25 35	>870 >870 >870	—	— 220 130	— 150 (90)	— 190 —	— 130 —	То же		

1/2-

TABLE 8

The fabrication of blades of titanium alloys (experience in the use of these alloys already exists in the aviation industry) is being planned for high-power turbines (300 Mw and higher)

These titanium-based alloys contain about 5% Cr and about 3% Al. The density of the alloy is $4,540 \text{ kg/m}^3$. Its mechanical properties are approximately the same as those of high-strength steels ($\sigma_{0.2} = 1,030 \text{ Mn/m}^2$; $\sigma_{0.2} = 980 \text{ Mn/m}^2$; $\delta = 15\%$; $\psi = 40\%$; BHN 3,150 n/mm^2 [24]), although the alloy is highly sensitive to scratches and marks which give rise to substantial concentration of stresses and reduce the fatigue strength of the metal.

Titanium alloys are very expensive.

Section 30. Materials for compressor and gas turbine blades

Compressor blades in existing gas turbines operate at temperatures below 300°C . Usually, intermediate air cooling is incorporated in turbines with increased rates of compression. Hence, the steels 1Kh13 and 2Kh13 (Table 8) are generally used for compressor blades. They have a high vibration damping decrement, an adequate corrosion resistance, and sufficiently high mechanical properties.

Gas turbine blades are fabricated either from chrome-nickel steels (EI726 and EI612K) or from nickel-based alloys (EI765, EI437, EI607, and EI893) (see Table 8).

It should be noted that the rupture strength of all these materials with 100,000 hours before failure is still very low at temperatures higher than 600°C . If the blade has a temperature of 700°C , then the material for it may be selected only if the stress in the blade does not exceed 100 to 120 Mn/m^2 (on the basis of the safety margin of 1.5 to 2 relative to the rupture strength). Alloy EI893, on whose characteristics little data has been published, is one of the most heat-resistant materials.

Aircraft turbines use materials which have high heat resistance and high temperature corrosion resistance (such as EI929, ZhS6-K, etc. [34]), making it possible to maintain the temperature of gases before the turbine at a level of 1000°C (without blade cooling and with a service life characteristic of aircraft engines). The materials are distinguished by their high cost and so far are not in use in stationary gas-turbine facilities.

Section 31. Materials for intermediate inserts, shrouds, and rivets

Blades with intermediate inserts are used only with low speeds and low temperatures. Stresses in the intermediate inserts are

completely insignificant, and hence the inserts may be fabricated from soft carbon steel (e.g., steel 15).

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Frequently, intermediate inserts are fabricated from steel 1Kh13 in order to avoid corrosion.

Steel 1Kh13 is used almost exclusively for shrouds and binding wire in modern Soviet turbines.

The wire is soldered with the brands PSr45 and PSr65 (Table 9) silver solder. An alloy of anhydrous potassium fluoride (43%) and boric acid (57%) serves as a soldering flux.

(1) Марка припоя	(2) Химический состав в %				(4) Темпера- тура плавления в °C	(5) Плотность в кг/м³	(6) Механические свойства	
	Ag	Cu	(3) Примеси не более	Zn			(7) σ _в в Мн/м²	(8) δ, %
(9) ПСр45	44.5— 45.5	29.5— 30.5	0.8	Осталь- (11)ное	720	9300	(12) Около 400	15—20
(10) ПСр65	64.5— 65.5	19.5— 20.5	0.8	Осталь- ное	740	9600	—	—

TABLE 9 Characteristics of Solders used for Soldering Binding Wires

(1) - Brand of solder; (2) - Chemical composition in %; (3) - Admixture, not greater than; (4) - Melting temperature in °C; (5) - Density in kg/m³; (6) - Mechanical properties; (7) - σ_v in Mn/m²; (8) - δ_{10} in %; (9) - PSr45; (10) - PSr65; (11) - Remainder; (12) - Approx.

Blades with Y-shaped roots are fastened to the wheel with rivets. The rivet heads are flattened on a special machine during assembly.

The rivets are often fabricated from the same material as the blades are under conditions of their adequate plasticity (1Kh13 and EI123).

Section 32. Selection of tolerable stresses

The strength criteria for blades may be yield strength σ' , fatigue strength σ_{-1} , creep limit $\sigma_{пл}$, and rupture strength $\sigma_{ДЛ}^{0.2}$.

The creep of a metal should be taken into consideration when the temperature is above 430°C for heat-resistant pearlite steels and above 480° to 520°C for austenitic steels.

The value of $\sigma_{0.2}^t$ is taken as strength criteria if the blades

* Index t signifies that the yield strength must be selected at the blade's working temperature.

operate at a temperature not exceeding the indicated values. Otherwise, the creep limit and rupture strength serve as the strength criteria.

By comparing the total stresses in the blade with any strength criterion, we establish the safety coefficients:

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$$K_T = \frac{\sigma_T}{\sigma_{\text{сумм}}}; K_{n_s} = \frac{\sigma_{n_s}}{\sigma_{\text{сумм}}}; K_{\partial_s} = \frac{\sigma_{\partial_s}}{\sigma_{\text{сумм}}}.$$

In this case the value $\sigma_{1/10^6}^t$ is usually assumed for the creep limit and the value $\sigma_{1/10^6}^t$ for the rupture strength if no special requirements are set.

The KhTGZ [44] recommends $K_T = 1.7$ only for tensile stresses at moderate temperatures, and at elevated temperatures

$$K_T = 2; K_{n_s} = 1.3; K_{\partial_s} = 2.$$

The tolerable stress (at elevated temperatures) is selected as minimum from three values:

$$\sigma_{\text{доп.расм}} = \frac{\sigma'_{0.2}}{K_T}; \sigma_{\text{доп.расм}} = \frac{\sigma'_{1/10^6}}{K_{n_s}}; \sigma_{\text{доп.расм}} = \frac{\sigma'_{\partial_s, 10^6}}{K_{\partial_s}}.$$

Here the bending stress on the blade due to the effect of the steam (gas) force should not exceed 35 Mn/m² for full blading and 15 Mn/m² for partial blading.

P.M. Mikhaylov-Mikheyev [24] recommends for coefficient $K_{\text{дл}}$ a value of 1.5 to 1.65 relative to the total stress in the blades.

This requirement involving the bending stress is governed by the fact that dynamic stresses arising during blade vibrations are difficult to evaluate. Since these stresses are directly proportional to the static bending stresses (Section 26), the magnitude of the latter should be limited.

There is a basis for suggesting that the figures indicated above pertaining to the tolerable bending stresses may be substantially increased. Bending stresses exceeding the indicated figures by a factor of 2 or more are permitted in constructed aircraft gas turbines (true, they have a small service life).

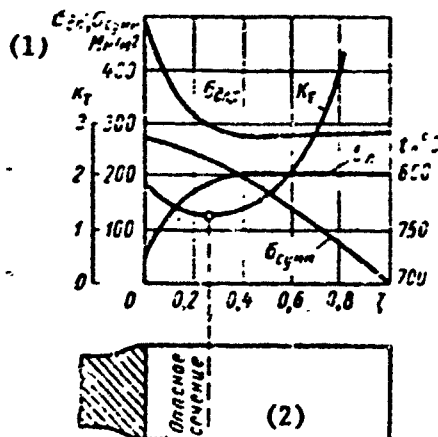


FIGURE 127

Variation of the safety margin along the length of a gas-turbine blade.

- (1) - $\sigma_0 + \sigma_{\text{sum}}$, Mn/m²;
(2) - Critical section

The overall tolerable stresses in the blade roots, shrouding, and binding wires according to data from the S.M. Kirov Khar'kov Turbogenerator Plant (KhTGZ) should be selected with the same margin of safety:

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$$K_T = 2; K_{\text{creep}} = 1.3; K_{\text{ten.str.}} = 2$$

The bearing stresses on the blade root and wheel contact surfaces are allowed to be great. For them:

$$K_T = 1.25; K_{\text{creep}} = 0.9; K_{\text{ten.str.}} = 1.25$$

Considering that the phenomenon of work hardening, which increases the rigidity of metal, develops in the pins of blades with a shrouding during the spreading of the latter, the KhTGZ recommends limiting the rupture stress in the pin's root to not more than 25 Mn/m² and the shear stress to not more than 20 Mn/m².

Gas-turbine blades in most instances are cooled by the removal of heat into the wheel. In that case, blade temperature t_{blade} varies along the length as shown in Figure 127 in accordance with what was stated in Section 16. The stress-rupture strength of the metal therefore increases toward the blade's base and increases faster over a certain length of the blade than the total stress σ_{total} . On the whole, the lowest safety margin may emerge not at the blade's base, where stress σ_{total} reaches maximum, but rather closer to the blade's middle. These circumstances must be taken into consideration during the design of gas-turbine blades.

Section 60. Materials for wheels and rotors. Selection of tolerable stresses.

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A turbine rotor is almost as much a strained component as the moving blades. A breakdown of the rotor is a serious emergency and is

frequently related with a complete breakdown of the turbine. Thus, the selection of a material for rotor elements (wheels, drums, fastenings) and the inspection of the materials must be done with special care.

The material for wheels, drums, and solid-forged and welded rotors must have:

- 1) high mechanical properties, including significant relative elongation, relative contraction, and impact strength;
- 2) sufficiently high stress-rupture strength and creep limit for high-temperature turbine stages;
- 3) a high heat-conduction coefficient and a low coefficient of linear expansion (this reduces the level of temperature stress) for high-temperature stages;
- 4) purity and homogeneity of composition;
- 5) absence of internal defects;
- 6) minimum level of internal stresses; and
- 7) good machinability.

The 3% nickel steel 34KhN3M (Table 20) is usually employed for heavy-loaded, shaft-mounted wheels in the low-pressure stages of steam turbines.

Steel 45 is satisfactory for less demanding circumstances (for low-power steam turbines and, of course, low temperatures).

Steel 34KhM is recommended by the KhTGZ [44] for wheels with thin blades and a relatively short boss. Wheels and components of welded rotors are frequently fabricated from that same steel.

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Solid-forged rotors of steam turbines operating at high temperatures are usually made of steels R2 (to temperature 540°C), EI415 (to 560°C), and EI802 (to 570°C). These brands of steels can also be used in the fabrication of mounted wheels in high-pressure stages of steam and gas turbines.

Austenitic steels are used for temperatures exceeding 570°C: EI405 to 600°C, EI726 and EI612 to 650°C, and EI612K to 700°C.

There is a marked tendency not to use austenitic steels since they have a low coefficient of heat conduction and a high coefficient of linear expansion. Thus, composite wheels have started being used in steam turbines (Section 34). Cooling gas-turbine wheels permits lowering their temperature and fabricating them from steels 34KhM, R2, or EI415 (Leningrad Metal Plant [LMZ], KhTGZ, Kaluga Turbine Plant [KTZ]).

The mechanical properties of the steels listed in Table 20 depend significantly on the heat treatment of the steels. Various heat treatment regimes make it possible to increase strength after reducing plastic deformations in the process, and vice versa.

The homogeneity requirements of the material for wheels and rotors are due to the high stresses in all parts of the wheel. For that reason, the mechanical properties of a material must be the same all over the disk, including in those parts originating from the central area of an ingot. As is well known, shrinkage porosities and nonmetallic inclusions are concentrated and an increased content of sulfur and phosphorus are noted in that area. Therefore, when forged pieces are received, specimens for mechanical testing are cut from the central portion of the wheel with the inner surface of the wheel bushing subject to a particularly careful investigation.

Internal stresses developing during stripping and improper heat treatment may lead to rupture of a wheel, even in the process of its fabrication. Specifications allow the following levels of internal stresses for steam-turbine wheels: not greater than 30 Mn/m^2 with a wheel diameter of up to 500 mm, not greater than 40 Mn/m^2 with a diameter of up to 1,000 mm, and not greater than 50 Mn/m^2 with a diameter greater than 1,000 mm. Internal stresses eliminate tempering of forged pieces with slow cooling in a furnace.

Good machinability of a material is characterized, on the one hand, by the material's hardness, which facilitates cutting the material, and on the other, by the ability to produce clean smooth surfaces without any roughness or scratches contributing to stress concentration.

TABLE 20 (following page)

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Chemical Composition and Mechanical and Physical Properties of Materials Used for Wheels, Solid-forged and Welded Rotors of Steam and Gas Turbines [22, 24]

(1) - Brand of material and its approximate chemical composition in %; (2) - Allowable temperature in $^{\circ}\text{C}$; (3) - Temperature of test sample in $^{\circ}\text{C}$; (4) - Physical properties; (5) - ρ in kg/m^3 ; (6) - λ in $\text{W/m} \times \text{deg}$; (7) - $\alpha \times 10^6$ in deg^{-1} ; (8) - Mechanical properties; (9) - $E \times 10^{-6}$ in Mn/m^2 ; (10) - σ_v [tensile strength] in Mn/m^2 ; (11) - $\sigma_{0.2}$ [yield point] in Mn/m^2 ; (12) - σ_5 [relative elongation] in %; (13) - ψ [relative contraction] in %; (14) - α_k [specific impact strength] in k-j/m^2 ; (15) - BHN; (16) - Stress-rupture strength in Mn/m^2 ; (17) - Creep in Mn/m^2 ; (18) - 34KhN3M; (19) - 34KhM; (20) - 25Kh1M1F(R2); (21) - 20Kh3MVF (EI415); (22) - 17Kh12VMF (EI802), Kh16N13M2B (EI405), Kh14N18V2BR1 (EI726); (23) - Kh15N35V3T (EI612); (24) - ET612K; (25) - See Table 8.

(1) Марка материала, его химический состав и механические свойства	(2) Допустимая температура в °C	(3) Температура испытания в °C	Физические свойства				Механические характеристики				Длинные прообразы					
			(5) ρ в кг/м ³	(6) α в 10 ⁻⁶ град ⁻¹	(7) μ в 10 ⁻⁶ град ⁻¹	(9) E в МПа	(10) $\sigma_{0.2}$ в МПа	(11) $\sigma_{0.2}$ в МПа	(12) $\sigma_{0.2}$ в МПа	(13) $\sigma_{0.2}$ в МПа	(14) $\sigma_{0.2}$ в МПа	(15) $\sigma_{0.2}$ в МПа	(16) $\sigma_{0.2}$ в МПа	(17) $\sigma_{0.2}$ в МПа	(18) $\sigma_{0.2}$ в МПа	
(18) 45 0,45 C; 0,27 Si; 0,65 Mn; 0,2 Cr; 0,3 Ni	300	20 200 400 500	7850	48,2 46,5 41,0 38,6	12,0 12,4 13,3 13,7	0,2 0,193 0,172 —	625 688 562 375	358 350 225 175	22,2* 10,3 21,3 23,5	49,6 36,0 65,2 67,0	460 636 748 390	143-200	— 245 68,5	— 186 43	— 111 40	— 81 27,5
(19) 34ХНМ 0,35 C; 0,27 Si; 0,65 Mn; 0,9 Cr; 0,3 Ni; 0,3 Mo	400	20 200 400 500	7830	41,1 37,7 30,6 —	10,8 11,6 13,7 —	0,207 — 0,172 —	955 905 860 620	860 760 690 540	18,7 15,7 21,0 18,3	49,3 59,9 69,8 75,0	1285 1490 1450 1010	270-300	— — — 132	— — — 68	— — — 98	— — — 34
(20) 25Х1М1Ф (P2) 0,25 C; 0,4 Si; 0,6 Mn; 1,6 Cr; 0,5 Ni; 0,7 Mo; 0,25 V	540	20 200 400 500 550	7820	40,6 39,8 37,3 — 27,0	12,3 12,6 13,9 14,3 13,77	0,214 — 0,191 0,182 —	655 610 530 440 460	465 420 390 353 560	19,5 16,0 17,0 18,0 19,0	52,5 52,0 64,0 74,0 61,0	735 1080 785 590 850	201-215	— — 206 — —	— — 148 — —	— — — — —	— — — — —
(21) 20Х3МВФ (ЭИ415) 0,2 C; 0,4 Si; 0,4 Mn; 0,4 V; 2,9 Cr; 0,5 Ni; 0,7 V; 0,45 Mo	500	20 200 400 450 500 600	7790	38,5 33,0 30,6 — 29,8 29,3	12,3 — — 12,6 12,75 13,82	0,207 0,2 0,186 0,181 0,186 0,164	875 785 780 615 640 475	745 695 660 615 610 490	19,8 12,4 9,3 11,6 11,1 9,7	49,3 51,6 33,4 45,0 44,0 23,1	370 660 860 960 745 620	240-290	— — — 435 360 108	— — — 390 330 67	— — — 245 170 21	— — — — — —
(22) 15Х15МФ (ЭИ182), X16H13M25 (ЭИ405), X14H16B2P1 (ЭИ7-6)	570 600 650	20 200 400 450 500 600	(25) См табл. 8	13,5 15,5 18,9 22,2 23,0	15,15 16,05 16,40 17,00 17,20	0,198 0,19 0,18 0,165 —	785 725 695 625 500	430 440 430 390 360	18 16 19 15 10	30 37 35 30 15	1080 1370 980 930 980	>200	— — — — 195	— — — — 157	— — — — 167	— — — 196 127
(24) ЭИ1612К	700		См табл. 8													

TABLE 20

As in the design of moving blades, the yield limit $\sigma_{0.2}^t$ is the strength criteria for the rotor elements: for pearlite steels at temperatures below 430°C and for austenitic steels at temperatures below 480° to 520°C. Along with these criteria, consideration must also be given to stress-rupture strength $\sigma_{n\lambda}$ after 100,000 hours and to creep limit $\sigma_{n\lambda}$ for 1% deformation after 100,000 hours during higher temperatures of the material. /262

Thus, for the tolerable stress in the elements of a rotor operating at moderate temperatures, it is assumed that

$$\sigma_{\text{tolerable}} = \frac{\sigma_{0.2}^t}{K_T}$$

in which KhTGZ recommends that the margin of safety K_T be assumed to equal 1.8 for mounted disks; 2.3 for disks of welded rotors; 3 for the connectors of these rotors in the welded area; and 2.2 for solid-forged rotors.

In all cases the quantity $\sigma_{0.2}^t$ must be taken at a working temperature.

In the temperature range in which the metal's creep (i.e., approximately at $t \geq 500^\circ\text{C}$) must be taken into account, the following must be determined in addition to the above indicated value of tolerable stress:

$$\sigma_{\text{tolerable}} = \frac{\sigma_{d\lambda}}{K_{d\lambda}} \qquad \sigma_{\text{tolerable}} = \frac{\sigma_{n\lambda}}{K_{n\lambda}}$$

where $K_{d\lambda} = 1.65$ and $K_{n\lambda} = 1.25$. The safety margin K_T recommended in this case is 2.2.

Section 70. Materials for Turbine and Compressor Shafts

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Shafts are fabricated in most cases from carbon open-hearth steel. Alloy steels are used for high stresses and particularly in high-pressure cylinders of turbines operating at considerable steam temperatures.

The specifications of steels used for shafts and the recommended brands of steel are shown in Table 21. The chemical composition of some of these brands was indicated in Table 16.

The materials used for solid-forged rotors (shafts and wheels forged together) are shown in Section 60.

(1) Тип стали	(2) Категория	(3) Предел прочности σ_b в МПа	(4) Предел текучести $\sigma_{0.2}$ в МПа	(5) Относительное удлинение δ_5 в %	(6) Относительное сужение ψ в %	(7) Ударная вязкость α_K в кДж/м ²	(8) Угол загиба в °	(9) Твердость HВ	(10) Позволяемая марка стали
(11) не менее									
Углеродистая	(12) I	510	280	19	40	390	180	149—207	35
Углеродистая	II	620	350	17	40	390	180	170—223	45
Легированная	(13) III	730	490	15	40	590	160	200—269	45X (14)
Легированная	IV	900	740	13	40	590	150	269—331	34XМ (15)

TABLE 21

Specifications of steels used for fabrication of turbine shafts

(1) - Type of steel; (2) - Category; (3) - Ultimate strength σ_b in Mn/m²; (4) - Yield point $\sigma_{0.2}$ in Mn/m²; (5) - Relative elongation δ_5 in %; (6) - Relative contraction ψ in %; (7) - Specific impact strength α_K in k-j/m²; (8) - Bending angle in degrees; (9) - BHN; (10) - Appropriate steel brand; (11) - not less than; (12) - Carbon steel; (13) - Alloy steel; (14) - 45Kh; (15) - 34KhM.

Section 97. Materials for Casings and the Selection of Tolerable Stresses

Turbine and compressor casings are cast from cast iron or steel or welded from sheet and section steel.

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Gray cast iron is a wide-spread and inexpensive material for casting compressors and low-temperature steam turbines. Cast iron brands SCh 15-32 and SCh 28-48, whose mechanical properties are shown in Table 31, are used for turbine casting.

(1) Марка	(2) Предел прочности в МПа при			(6) Стрела прогиба на длине 600 мм в мм	(7) Твердость по Бринеллю
	(3) растяже- нии	(4) изгибе	(5) сжатии		
СЧ 15-32 (8)	15	32	65	8	163—229
СЧ 28-48 (9)	28	48	90	9	130—170
МСЧ 32-52 (10)	32	52	100	9	170—241

TABLE 31

Requirements placed on cast iron

(1) - Brand; (2) - Ultimate strength in Mn/m² during; (3) - tension; (4) - Bending; (5) - Compression; (6) - Bending deflection in mm for a 600-mm length; (7) - Brinell Hardness Number; (8) - SCh 15-32; (9) - SCh 28-48; (10) - MSCh 32-52.

Ordinary cast irons are subject to the phenomenon of growth at high temperatures. With iron carbide decomposition and precipitation of free graphite, the casting increases in volume (grows), becoming porous and significantly losing strength. The phenomenon of growth of cast iron is noted at temperatures of approximately 160°C and higher. The growth intensity rises with an elevation in temperature and with time the cast iron is under the effect of high temperature. Therefore, cast iron is more frequently used for working at a temperature not exceeding 250°C.

However, use is currently being made of special brands of cast irons of a pearlite structure which do not show growth, even at temperatures higher than those indicated above.

Grouped with such materials are the so-called inoculated cast irons, i.e., cast irons with the addition of inoculants which graphitize the cast irons and give them a fine-grained texture. Inoculated cast irons maintain almost unchanged their mechanical properties at elevated temperatures of up to 500°C, and at temperatures ranging from 400°C to 500°C their tensile strength and impact strength even increase.

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The characteristics of the inoculated cast iron MSCh 32-52 are given in Table 31.

The possibility of using inoculated cast iron for prolonged operation at a temperature exceeding 300°C so far has not been demonstrated.

Steel casting is used almost exclusively for high- (and occasionally medium-) pressure casings.

Castings operating at temperatures up to 450°C can be fabricated from carbon steel.

Steel 25L (Table 32) is in very widespread use. Its stress-rupture strength at a temperature of 400°C is just 150 Mn/m², which must be taken into consideration when selecting the tolerable stress.

Chromium-molybdenum steel 20KhML may be used with a steam temperature of 500°C. At a temperature of 500°C, $\sigma_{V,10^5} = 160 \text{ Mn/m}^2$; beyond that, both the stress-rupture strength and creep limit drop sharply.

Far better mechanical properties are found in chromium-molybdenum-vanadium steel 20KhMFL capable of being used at a temperature of 580°C which so far is limiting for pearlite steels. It should be noted that at 580°C, $\sigma_{V,10^5}$ is only about 70 Mn/m^2 . For a steam temperature of up to 565°C, the LMZ also recommends chromium-molybdenum-vanadium steel 15Kh1M1FL of the pearlitic structure.

Austenitic steels should be used at temperatures higher than 560° to 580°C. Steels LA1, LA3, LA4, and LA5 are being used for casting casings in steam-turbine construction. The first two brands are almost identical in terms of their mechanical properties, although steel LA1 is recommended for temperatures up to 650°C and steel LA3 up to 600°C (at this temperature $\sigma_{V,10^5} = 140 \text{ Mn/m}^2$). Steel LA5 is designed for extended service at temperatures up to 700°C, although $\sigma_{V,10^5}$ in this case is only about 60 Mn/m^2 .

Steel 15Kh11MVFL suitable for operating up to 600°C shows promise. However, its stress-rupture strength at 600°C is only 78 Mn/m^2 .

A comparison of the physical properties of pearlite steel 20KhMFL and austenitic steel LA3 is shown in Table 32. As can be seen, the former has a significantly smaller coefficient of linear expansion but greater thermal conductivity at low temperatures. In this case, thermal conductivity of steel 20KhMFL drops while that of steel LA3 increases slightly with a temperature elevation.

Information on the relaxation stability of some steels used for fastening elements is given in Table 33.

(1) Марка материала и его примерный химический состав в %,	(2) Допустимая температура в °С	(3) Температура испытания в °С	(4) Физические свойства			(8) Механические характеристики							(15) Лимитная прочность	(17) Предел прочности
			(5) ρ в кг/м ³	(6) α в см/(м·град)	(7) $\mu \cdot 10^{-6}$ в град	(9) $E \cdot 10^{-10}$ в МПа/м ²	(10) σ_b в МПа/м ²	(11) $\sigma_{0.2}$ в МПа/м ²	(12) σ_s в %	(13) δ_5 в %	(14) δ_{10} в %	(16) $\sigma_{0.1\%}$ в МПа/м ²	(18) $\sigma_{1/2\%}$ в МПа/м ²	
(19) Сталь 20 0,2 С; 0,17 Si; 0,5 Mn	350	20 350	7850 42	50,6 42	11,6 13	0,2 0,17	431 350	255 147	26 26	55 78	1270 880	150	90	
(20) 25Л 0,26 С; 0,27 Si; 0,65 Mn	400	20 400	7830 42	47 42	11,5 13,1	0,2 0,17	441 350	235 160	19 16	35 55	392 770	150	70	
(21) 20ХМЛ 0,22 С; 0,3 Si; 0,65 Mn; 0,5 Mo; 0,55 Cr; 0,3 Ni	500	20 400 500	—	49 31 28	10,9 13,1 13,6	—	460 430 390	300 340 295	18 19 22	30 59 62	600 790 830	160	80	
(22) 20ХМФЛ 0,21 С; 0,28 Si; 0,5 Mn; 0,6 Mo; 1,05 Cr; 0,25 V	580	20 475 550	7800	49 28 25	10 13,5 13,7	0,2 — 0,17	490 440 300	310 250 225	20 19 18	35 46 61	340 900 550	210 120	160 50	
(23) 15Х1М1ФЛ 0,17 С; 0,27 Si; 0,55 Mn; 1 Mo; 1,45 Cr; 0,3 V	580	20 580	— —	— —	— —	— —	490 —	343 —	14 —	30 —	294 —	78	39	
(24) 15Х1М1ФЛ 0,16 С; 0,1 Si; 0,75 Mn; 0,6 Mo; 11 Cr; 0,65 Ni; 0,22 V; 0,95 W	600	20 600	— —	— —	— —	— —	588 —	400 —	15 —	50 —	490 —	78	39	
(25) ЛА3 0,16 С; 0,55 Si; 1 Mn; 2 Mo; 14 Cr; 14 Ni; 1,5 W; 0,5 V; 0,4 Nb; 0,2 Ti	600	20 580 650	8065	16,5 22,5 29,5	— 17,4 17,6	0,196 0,153 —	450 330 330	200 140 140	20 23 24	— — —	450 — —	155 115	120 60	
(26) 1Х18Н9Т (ЭИ1Т) 0,12 С; 0,8 Si; 2 Mn; 12 Cr; 0,2 Ni; 0,8 Ti	600	20 600	7900	16,3 29,6	16,6 18,2	—	510 —	200 —	10 —	55 —	590 —	80	130	
(27) 20ХМ** 0,36 С; 0,27 Si; 0,5 Mn; 1 Cr; 0,2 Mo	450	20 450	7820	46,6 31	12,3 14,1	0,209 —	1000 880	880 —	12 —	15 —	780 —	120	100	
(28) 25Х2МФА** (ЭИ10) 0,25 С; 0,27 Si; 0,5 Mn; 1,6 Cr; 0,3 Mo; 0,2 V	500	20 500	7840	42 38	11,3 14	0,212 —	835 —	735 —	15 —	50 —	590 —	180	80	

(30) * Свойства сталей X16H13M2B (ЭИ1405), X16H13M2B (ЭИ1412), 1X13, 2X13 см. в табл. 8 и 20.

(31) ** Эта сталь, а также стали 45 и X15H17P15M1K2TP (ЭИ1765) применяются для крепящих деталей; на свойства см. в табл. 8 и 20.

TABLE 32

Chemical Composition and Mechanical and Physical Properties of
Materials Used for Stator Elements of Steam and Gas Turbines

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(1) - Brand of material and its approximate chemical composition in %;
 (2) - Tolerable temperature in °C; (3) - Testing temperature in °C;
 (4) - Physical properties; (5) - ρ in kg/m³; (6) - λ in w/(m x deg);
 (7) - $\alpha \times 10^6$ in deg⁻¹; (8) - Mechanical properties; (9) - $E \times 10^{-6}$
 in Mn/m²; (10) - σ_v in Mn/m²; (11) - $\sigma_{0.2}$ in Mn/m²; (12) - σ_s in %;
 (13) - ψ in %; (14) - α_H in k-j/m²; (15) - Stress-rupture strength;
 (16) - $\sigma_{v,10^5}$ in Mn/m²; (17) - Creep limit; (18) - $\sigma_{v,10^5}$ in Mn/m²; (19) -
 Steel 20; (20) - 25L; (21) - 20KhML; (22) - 20KhMFL; (23) - 15Kh1M1FL;
 (24) - 15Kh11MVFL; (25) - LA 3; (26) - 1Kh18N9T (EYalT); (27) - 30KhM**;
 (28) - 25Kh2MFA**(EI10); (Continuation of Table 32); (30) - *For the
 properties of steels Kh16N13M2B (EI405), Kh15N35V3T (EI612), 1Kh13,
 and 2Kh13 see Tables 8 and 20.; (31) - **This steel and steels 45 and
 Kh15N70V5M4Yu2TR (EI765) are used for fastenings; for their properties
 see Tables 8 and 20. /403

(1) Марка стали	(2) Температура в °C	(3) Начальное напряжение σ_0 в Мн/м ²	(4) Конечное напряжение σ_K в Мн/м ² за время τ		
(6) 35ХМ	400	150 250 350	(5) 3000 ч	5000 ч	10 000 ч
			57	53	45
			84	77	64
			109	98	82
(7) ЭИ110	500	120 250 350	63	78	70
			162	152	139
			222	215	190
(8) ЭИ765	565	250 300 350	6000 ч	10 000 ч	12 000 ч
			225	220	220
			278	270	270
			310	310	310
	600	250 300 350	205	210	200
			260	260	250
			305	300	300
(9) ЭИ612	650	150 200 250	3000 ч	8000 ч	10 000 ч
			121	115	112
			156	143	140
			184	166	160

TABLE 33

Relaxation stability of steels used for fastenings [44]

(1) - Brand of steel; (2) - Temperature in °C; (3) - Initial stress σ_0 in Mn/m²; (4) Final stress σ_K in Mn/m² after time τ ; (5) - 3,000 hours; (6) - 35KhM; (7) - EI10; (8) - EI765; (9) - EI612

For cast iron elements of turbine and compressor casings, the KhTGZ [44] recommends that the safety margin at moderate temperatures be $K_T = 2^*$ where

$$K_T = \frac{\sigma_{0.2}^t}{\sigma_{\text{tolerable}}}$$

* See Section 32 for designations.

At elevated temperatures, the tolerable stress is selected from three quantities as a minimum:

$$\sigma_{\text{tolerable}} = \frac{\sigma_{0.2}^t}{K_T}; \quad \sigma_{\text{tolerable}} = \frac{\sigma_{\text{дл}}}{K_{\text{дл}}}; \quad \text{and} \quad \sigma_{\text{tolerable}} = \frac{\sigma_{\text{пл}}}{K_{\text{пл}}}$$

in which $K_T = 2$; $K_{\text{дл}} = 2$; $K_{\text{пл}} = 1.55$.

The coefficients for forged casing elements are $K_T = 1.65$; $K_{\text{дл}} = 1.65$; and $K_{\text{пл}} = 1.25$.

For castings made of grey cast iron, the tolerable stress is selected on the basis of tensile strength σ_V :

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$$\sigma_{\text{tolerable}} = \frac{\sigma_V}{K_V}$$

For a working medium temperature not exceeding 250°C, $K_V = 4.5$.

Bolts fastening casing components and subject to low temperatures (not higher than 300° to 320°C) may be fabricated from carbon steel 34 or 45.

Chromium-molybdenum steels 30KhM, 35KhM, and EI10, and also steels EI765 and EI612 (see Table 15) are recommended for higher temperatures.

At moderate temperatures, the safety margin may be $K_T = 2$ relative to creep limit $\sigma_{0.2}^t$.

The strength criteria of fasteners subject to high temperatures (higher than 350° to 400°C) under stress relaxation conditions have not been worked out sufficiently at present. The creep process in this case occurs at variable stresses: stresses vary from σ_0 to σ_k during each period between tightenings of the fasteners. Accordingly, the creep rate also changes. Under certain assumptions, Ye. A. Kheyn [sic] [40] obtained formulas for the equivalent constant stress σ_e which gives rise to material deterioration over the same time interval as do variable stresses.

If one considers that the rate of the steady-state creep is governed by equation $v = B\sigma^t$, then

$$\sigma_e = \sigma_K \sqrt[t]{\frac{(t-1)(v-1)}{1 - \frac{1}{v^{t-1}}}} \quad (527)$$

where $v = \frac{\sigma_0}{\sigma_K}$.

Described somewhat better is the process of relaxation using the equation

$$v = B_1 sh n\sigma.$$

In this case

$$\sigma = \frac{\sigma_0 + \sigma_K}{2} - 0.001 (\sigma_0 - \sigma_K)^2 \quad (528)$$

with $0 \leq (\sigma_0 - \sigma_K) \leq 140 \text{ Mn/m}^2$;

$$\sigma_e = \frac{\sigma_0 + \sigma_K}{2} - 0.07 (\sigma_0 - \sigma_K) - 0.0005 (\sigma_0 - \sigma_K)^2 \quad (529)$$

and $140 \leq (\sigma_0 - \sigma_K) \leq 340 \text{ Mn/m}^2$.

After selecting the quantity σ_K using formulas (523), (524) or Table 33, quantity σ_0 is arrived at, and then the value of the equivalent stress σ_e is computed using formulas (527) to (529). /406

This value is then compared to the stress-rupture strength at a given temperature and time which is equal to the entire length of service of the turbine, i.e., not less than 100,000 hours.

Thus, the strength condition of fastening elements (pins, bolts) is written as follows:

$$\sigma_e \leq \frac{\sigma_{v, 10^5}}{K}.$$

where the safety margin $K \geq 2$.

The initial stresses σ_0 must also be smaller than the yield point $\sigma_{0.2}$ by at least a factor of 2. It must be emphasized that excessively large margins of safety are undesirable since they result in oversized flanges.

Section 101. Materials for Diaphragms in Steam Turbines and the Selection of Tolerable Stresses

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Cast irons SCh 18-36, SCh21-40, and SCh24-44 may serve as the material for cast-iron diaphragms. These cast irons are used at temperatures up to 250°C. The tolerable stress for them is selected with a safety margin of 5 to 6 relative to the ultimate strength during bending. Thus, for cast iron SCh 18-36, for example, $\sigma_{\text{bend}} = 60$ to 70 Mn/m² may be tolerated.

Pearlite cast iron SCh 28-48 or inoculated cast irons in which the stress may be brought up to 100 Mn/m² can be used at temperatures to 300°C.

With increased temperatures, steel diaphragms are used.

Diaphragms made of forged steel 30 are used for temperatures not exceeding 350° to 360°C. The tolerable stress in them may be up to 150 Mn/m² at a temperature of about 200°C and up to between 70 to 80 Mn/m² at a temperature of 350°C.

Usually, chromium-molybdenum steels 15KhM, 20KhM, and 35KhM are used for operating at high temperatures. By assuming the tolerable creep rate to be 10⁻⁶% per hour, a stress of up to 80 Mn/m² at a temperature of 350°C may be considered tolerable for these steels. Diaphragm blades stamped from sheets are fabricated almost exclusively from steel 1Kh13M. That same steel and also steels 1Kh13 and 2Kh13 are used for milled blades.

The tolerable stress in cast blades is small: 40 to 50 Mn/m².

The KhTGZ [44] recommends the following safety margins for the body and blades of diaphragms: $K_T = 1.65$ to 3; $K_{\text{дп}} = 1.65$ to 2.3; and $K_{\text{лп}} = 1.25$ to 1.4, in which

$$K_T = \frac{\sigma_{0.2}^*}{\sigma_{\text{tolerable}}}; K_{\text{дп}} = \frac{\sigma}{\sigma_{\text{tolerable}}}; K_{\text{лп}} = \frac{\sigma}{\sigma_{\text{tolerable}}}.$$

It should be noted that the figures for the lower limit must be used for an accurate design of a diaphragm. The upper limit figures are based on a broad statistical analysis of diaphragms of operating turbines.

Diaphragm deflection should not exceed 1/3 of the gap between the diaphragm and the wheel.